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Seat-integrated localized ventilation for exposure reduction to air pollutants in indoor environments

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ABSTRACT
A novel ventilation method for minimizing the spread of bioeffluent contaminants generated from sedentary people indoors was developed and studied. The concept of the method consists of a ventilated cushion which is able to suck the human bioeffluents at the area of the body where they are mainly generated before they disperse around a room. The polluted near the body air is exhausted into the cushion and it is removed from the room by a separate exhaust system. The performance of the method was studied in series of experiments. Full-scale room and a dressed thermal manikin sitting in front of a desk were used to simulate one person office. The chair on which the thermal manikin was sitting had the ventilated cushion (VC). Tracer gases, carbon dioxide (CO_2) and nitrous oxide (N_2O), were used to simulate bioeffluents emitted by the manikin's armpits and groin region respectively. The experiments were conducted at 26°C room air temperature. The performance of the VC in conjunction with mixing total-volume background ventilation at 1 air change per hour (ACH) was compared with that of mixing background ventilation alone operating at 1, 1.5, 3 and 6 ACH. Experiments at exhaust airflow rate from the cushion at 1.5, 3 and 5 L/s were performed. The pollution removal efficiency was assessed by measuring the pollution concentration in the breathing zone of the manikin and at several other locations in the room bulk air. Exhausting air through the VC decreased the concentration of the tracer gases at the breathing zone and in the room. The higher the exhaust flowrate, the more the concentration was decreased.

KEYWORDS
Indoor air quality, human bioeffluents, exposure, localized exhaust ventilation

INTRODUCTION
People spend most of the time in indoor environments such as office buildings, at home, vehicle compartments, etc. Occupants' health, well-being and productivity in these environments are affected by the indoor air quality (IAQ) (Wargocki et al. 1999, Zhang et al. 2016). Primary pollution sources in indoor premises can be the occupants themselves (Zhang et al. 2016). Human metabolism not only produces carbon dioxide (CO_2) but also generates odorous gaseous compounds (bioeffluents), which are volatile organic compounds (Wang et al. 2014). Volatile organic compounds (VOCs) are one of the bioeffluents that are emitted from the skin. Production of VOCs by the human skin is governed mainly by the secretion of apocrine and sebaceous glands (Noël et al. 2012). Apocrine glands are located in the axillae, genital area and areolas. Secretions from these glands provide favourable environment for numerous populations of bacteria which are considered main contributors to the formation of human body odor (Dormont et al. 2013).

It has been reported that heating ventilation and air-conditioning (HVAC) equipment accounts for nearly 40 percent of total global building energy consumption (Navigant Consulting 2016). The most commonly used method to reduce the indoor contaminants in the air is by means of mechanical (forced) ventilation. The current total volume air distribution principles (i.e. mixing and displacement) should supply large volume of filtered outdoor air to the entire space to dilute or remove the contaminants from the occupied zone. This method is highly inefficient (Melikov 2016) and uses significant amount of energy to exchange the air in a room.

To obtain high quality indoor environments at reduced background ventilation rate, different advanced local ventilation systems have been developed and studied (Melikov 2016). Recently, experimental studies (Bivolarova et al. 2016, Bivolarova et al. 2014) examined the effectiveness of using local exhaust ventilation to remove body generated bioeffluents while a person is in bed and thus to reduce the indoor exposure to those pollutants. A ventilated mattress with suction openings below the feet and the groin area of a thermal manikin was used. The results showed that the use of the ventilated mattress at 1.5 L/s together with background ventilation rate of 1.5 air changes per hour (ACH) improved the air quality in the room and the breathing zone compared to when the background ventilation was used alone at 6 ACH (Bivolarova et al. 2014).

The present study aimed to implement local exhaust ventilation into a cushion for a seat and to identify its efficiency for capturing body-emitted bioeffluents in a single office environment.

METHODS

The experiment was performed in a test room furnished to simulate a single office room. The dimensions of the room were 5.9 m x 6 m x 3.2 m (W x L x H). A typical office working environment was simulated by a thermal manikin seated on a computer chair in front of a desk with a laptop on it (Figure 1). The room had 12 ceiling mounted light fixtures (32 W each) spread over the entire ceiling.

Mixing air distribution was used to supply 100% outdoor air to the room through a square diffuser mounted in the middle of the ceiling. No recirculation was used during the experiments. During the measurements, summertime conditions were maintained in the office room. The air temperature in the room was kept 25.5 °C ±0.5 °C. Series of experiments were conducted at four background ventilation rates -1, 1.5, 3 and 6 ACH. Two different four way supply diffusers were used: Ø160 (sizes 295 mm x 295 mm) for 1 and 1.5 ACH ventilation rates and Ø250 (sizes 495 mm x 495 mm) for 3 and 6 ACH. In both cases the diffuser was supplying the outdoor air in three directions (position 7 in Figure 1). One of the air supply slots of the diffuser was blocked in order to avoid possible short circuit with the exhaust. To exhaust the air from the room, a rectangular exhaust grill (sizes 970 mm x 170 mm) mounted on the wall close to the ceiling was used (position 8 in Figure 1).

The office room was assumed to be located in a low-polluting building. According to the European Standard EN 15251 (2007) the ventilation rate required for diluting emissions (pollutants) from the building components (building and furnishing, and HVAC system) is 0.7 L/s per m^2 floor area for IAQ category II and 1 L/s per m^2 floor area for IAQ category I. The required ventilation rate for diluting emissions (bio-effluents) from people is 7 L/s per person for IAQ category II and 10 L/s per person for IAQ category I. The total required ventilation rate for each category is the sum of these two calculated ventilation rates. The required total ventilation rate for the simulated single office in this study (35.4 m^2 floor area and 1 occupant in the room) was calculated to be 31.8 L/s (1 ACH) for category II and 45.4 L/s (1.5 ACH) for category I. The new localized ventilation system was operated only with the background ventilation of category II. Additionally, two more cases at high background ventilation rates were performed - 94.4 L/s (3 ACH) and 188.8 L/s (6 ACH).

A dressed thermal manikin with realistic human body size, shape, and surface temperature distribution was used as a sitting occupant. The manikin was dressed in panties, short sleeve shirt, normal trousers, normal socks and thin soled shoes with the overall thermal insulation of 0.47 clo (DS EN ISO 7730 2005). The thermal manikin maintained the same sensible heat as that released by a healthy average person in a state of thermal comfort.

The manikin was sitting on a ventilated cushion which was placed on a computer chair (Figure 2). The ventilated cushion (VC) was used in some of the experiments to exhaust locally simulated contaminants emitted from the manikin's body. Along the surface of the VC there were eight rows of small openings each with diameter of 6 mm. There were two openings per row and the distance between them was 0.135 m. The VC was connected to a local exhaust which was able to suck air through the openings and exhaust it out of the room (Figure 1). There was a mesh inside the ventilated cushion which provided support and allowed the exhaust air to move through the cushion. During the measurements, the exhaust airflow rate of the VC was provided by an axial fan connected to the VC with flexible and straight ducts (Ø 0.08 m). The airflow rate through the VC was measured with an air flow sensor (MFS-C-0080) installed in the straight connection between the fan and the VC. The maximum error in the measurement with this sensor is ±3 % of the actual flow. The pressure difference at the MFS sensor was measured with a differential pressure micro-manometer FCO510 (accuracy of 0.01 Pa [0.15×10^{-5} psi] ±0.25% of reading). Based on the pressure difference readings from the micro-manometer, the desired flow rate was adjusted by a manually operated damper. The performance of the VC was tested at three exhaust flow rates - 1.5 L/s, 3 L/s and 5 L/s.

Tracer gases, namely carbon dioxide (CO_2) and nitrous oxide (N_2O), were used to simulate bioeffluents emitted by the manikin's armpits and groin region respectively. The tracer gases were dosed at constant emission rates directly from compressed gas cylinders. The gas was transported from the cylinders to the manikin through separate pipes and released through porous sponges that were fixed to the end of the pipes and attached to the polluting body parts. The emission rate of CO_2 and N_2O were adjusted to be 0.4 L/min and 0.1 L/min respectively. The air mixed with the tracer gases was sampled and its gas concentration was analysed under steady-state conditions using two Innova 1303 multi-channel samplers and two photoacoustic multi-gas monitors Innova 1312. The instruments were calibrated prior to the experiments and the gas detection limits after calibration were defined 5 ÷ 3500 ppm and 0.5 ÷ 350 ppm for CO_2 and N_2O respectively. The instruments were placed outside the test room. The gases were sampled through nylon tubes in diameter 4 mm. The concentration of each tracer gas was measured at six measuring points: at the breathing zone of the manikin, 0.5 m above the head, at the supply, total exhaust air, and in the centre of the room at 1.7 m height. At each sampling point, 40 values of the tracer gas concentration were collected after reaching steady state.

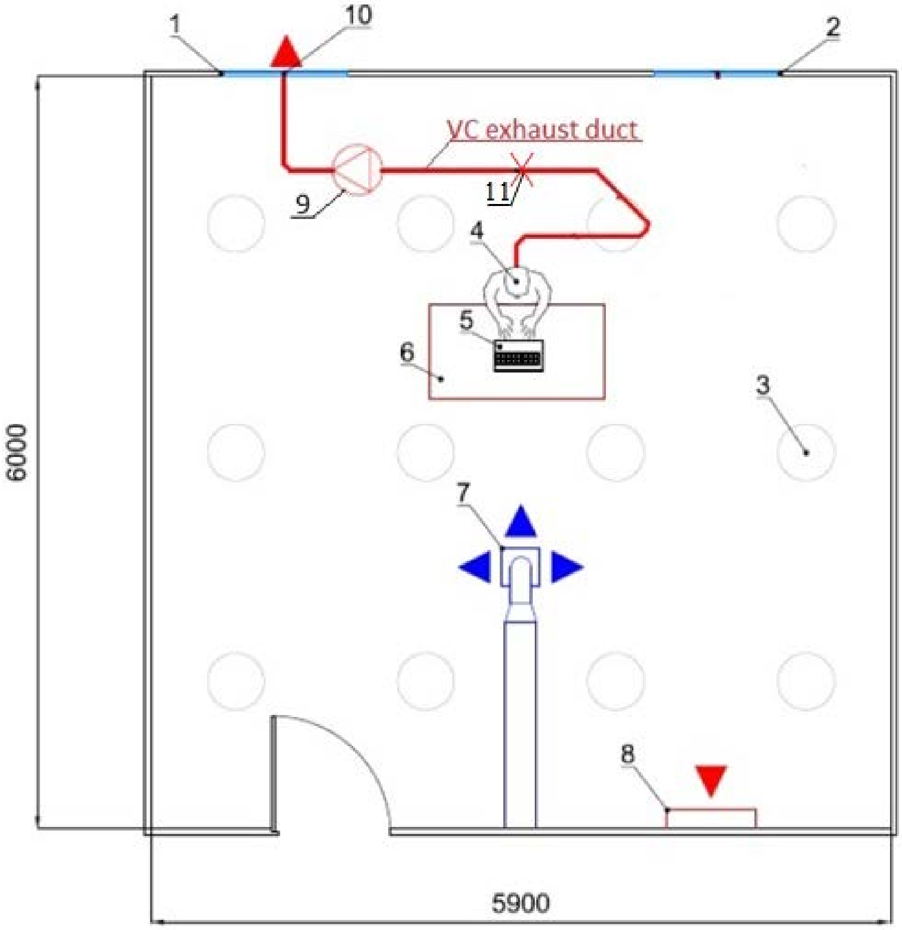


Figure 1. Room layout: 1; 2 – windows, 3 – lights (12 in total), 4 – occupant, 5 – laptop PC, 6 – table, 7 – supply, 8 – total exhaust, 9 – fan, 10 – air exhaust, 11 – air flow sensor MFS-C-0080.

Figure 2. The ventilated cushion (VC) positioned on the computer chair and connected to the exhaust duct.

In order to assess the efficiency of the VC in removing body bioeffluents, the measured concentrations were normalized as follows:

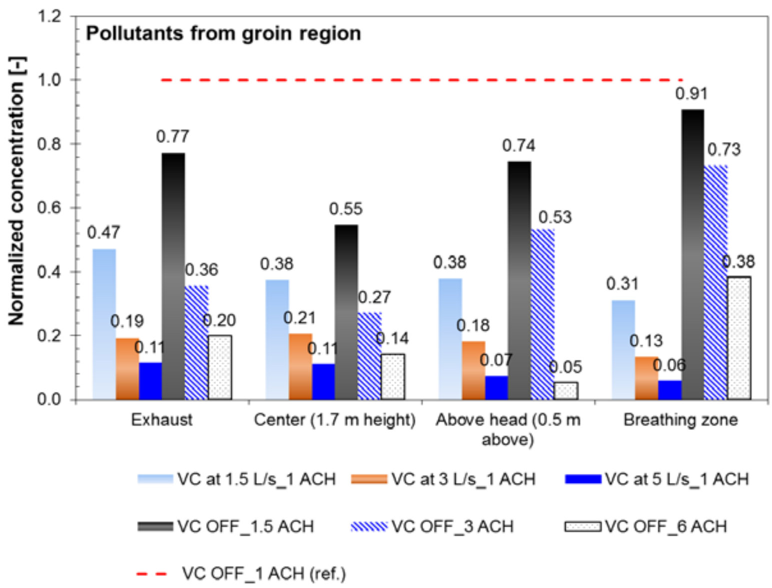
Normalized concentration = $C_{i,avg}/C_{i,avg,Ref}$ (1)

where $C_{i,avg}$ is the average concentration measured at the sampling location during each of the studied conditions; $C_{i,avg,Ref}$ is the average concentration measured at the same sampling location during the reference condition when the VC was not operating at 1 ACH background ventilation rate. The value of the normalized concentration lower than "1" shows that the concentration of the contaminants at the measuring point is lower compared to the reference case (i.e. improvement of air quality) and vice versa when the value is higher than "1". For the reference case the normalized concentration is equal to 1.

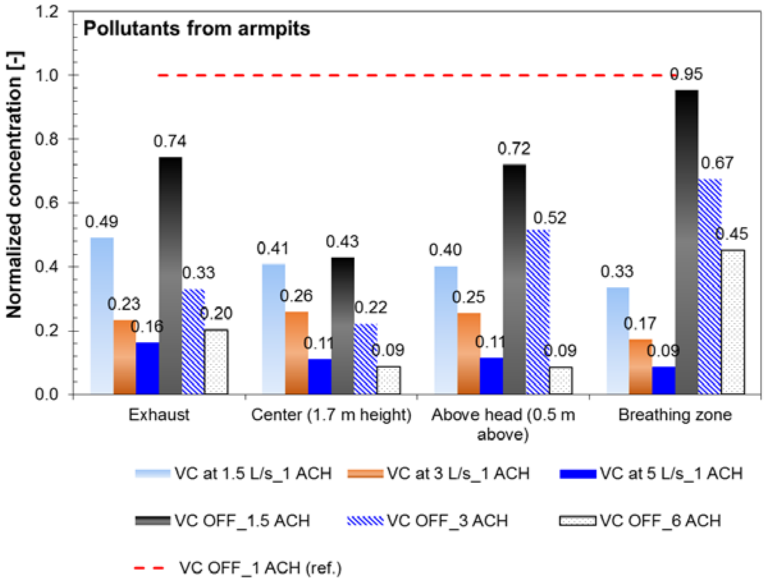
RESULTS

The results of the normalized concentrations at all measured locations for both pollution sources (armpits and groins) are shown in Figure 3a and 3b respectively. Results obtained at background ventilation of 1.5, 3 and 6 ACH with VC turned OFF and when the VC operated at 1.5, 3 and 5 L/s at background ventilation of 1 ACH are shown. The results in Figures 3a and 3b show that the normalized values are the highest at the mouth of the thermal manikin. In both figures there is a clear trend of the pollution concentration decreasing as the exhaust flowrate through the VC increased. Similarly, the concentrations decreased as the mixing background ventilation rate increased and the VC was not working. The results show that when the VC was exhausting air at 1.5 L/s the concentration of the pollutants generated from the groin region was reduced by 69% in the mouth compared to the reference case. By increasing the exhaust flow rate to 3 L/s, the reduction of concentration reached 87%. The concentration of the pollutants was reduced by 94% when the VC was operating with 5 L/s exhaust flowrate. The same concentration reduction, with respect to the reference case, was observed in the other measured locations for both pollution sources (armpits and groins), differing from each other by about ±9 %.

What is interesting in this data (Figure 3a and 3b) is that supplying 188 L/s (or 6 times) more clean air into the room was less efficient to reduce the concentration of the pollutants in the breathing zone than exhausting 1.5 L/s air from the VC and supplying 32 L/s into the room.



a)



b)

Figure 3. Average concentration at all measuring points a) dosing from the groin region and b) dosing from the armpits.

DISCUSSIONS

Overall, the results from the current study show that when the ventilated cushion (VC) is in operation, the concentration of the pollutants released from the groins and the armpits of the thermal manikin decreased at the measured locations. This is because the body of the thermal manikin was in contact with the cushion. Higher exhaust flow rate through the VC increase the suction of the air that allows more pollutants to be captured and removed before they are spread in the room.

The results show that in comparison with the condition without VC and the background ventilation at 1.5 ACH (45.4 L/s), the concentration of the pollutants emitted from the thermal manikin (groins and armpits) decreased in the breathing zone by about 65% when the VC was working at exhaust flowrate of 1.5 L/s and background ventilation at 31.8 L/s. In the total exhaust air of the room the decrease was by more than 30% when using the VC at 1.5 L/s compared to the concentrations at 1.5 ACH VC OFF. It means that when the VC was in use, better IAQ was achieved by transporting about 12 L/s less air (1.5 L/s instead of 13.6 L/s). According to the European Standard EN 15251 (2007) background ventilation rate of 45.4 L/s (1.5 ACH) corresponds to IAQ of category I for a single office in a low polluting building. It can therefore be assumed that the implementation of the VC would provide better air quality at lower ventilation rate per person. This may lead to energy savings. Further studies, which take the energy use into account, will need to be undertaken.

The results for both simulated air pollutants, namely groins and armpits, showed that the concentrations at the mouth are higher than the concentrations measured above the head and in the exhaust of the room. This is because the breathing zone is closer to the body-emitted pollutants. It has been reported that the natural convective flow around a seated person has the ability to transport gaseous pollutants released from the body upward to the breathing zone and above the head (Licina et al. 2014). Therefore, the self-exposure of these pollutants is rather high. The concentrations of the pollutants at the mouth are important as they directly influence the inhaled air quality. Therefore, it is expected that the VC will improve the quality of inhaled air in terms of body-emitted gaseous pollutants since it will reduce their transport by direct local exhaustion.

It should be noted that the practical application of the VC may be changed under different room conditions and occupant behavior. The current study does not consider different body postures, human respiration, different outfits and physical movements when a person is sitting. Several issues, related to control and optimization of the VC as well as human response remain to be studied. It should be noted that a filter can be easily incorporated inside the VC, where the polluted air will be cleaned locally and discharged it back into the room. This method was shown by Bivolarova et al. (2016). The “plug and play” method can be applied, which will prevent the use of additional ducting. This will increase the flexibility of the chair and it will be possible the chair equipped with the VC to be moved without difficulty.

CONCLUSIONS

This study investigates the performance of the ventilated cushion with regard to indoor air quality. The experimental results reveal the following:

- Exhausting air through the VC decreased the concentration of pollutants, released from the groin and armpits region of the simulated person, at the breathing zone and in the room. The higher the exhaust flowrate, the more the concentration was decreased.
- Exhausting 1.5 L/s of air through the VC at 1 ACH in the room to reduce the bioeffluents’ concentration at the breathing zone was about 65% more efficient than proving the recommended 1.5 ACH for category I IAQ in low polluting building.
- The use of the VC not only can improve the air quality by reducing the unpleasant body odors, but also may lead to energy savings due to deduced background ventilation rate.

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